LHC Upgrade Scenarios and Requirements

see LHC Project Report 626

July–September 2001: LHC Luminosity and Energy Upgrade – an order of magnitude in luminosity and a factor two in energy – feasibility study by a CERN task force

11-12 March 2002: LHC IR Upgrade collaboration meeting, see web site at `http://cern.ch/lhc-proj-IR-upgrade`

8-11 October 2002: ICFA Seminar on 'Future Perspectives in High Energy Physics', CERN

- scenarios for a staged LHC upgrade
- upgrade of the Interaction Regions
- upgrade of the LHC Injectors
- upgrade of cryogenics, vacuum, RF, and beam dump systems
- recommendations for further beam dynamics studies and R&D

LHC Luminosity and Energy Upgrade: CERN Feasibility Study

Several scenarios have been considered by the task force, including

- minor and major hardware changes in the LHC and its injectors
- the role of synchrotron radiation and Intra-Beam Scattering
- the electron cloud build-up for various bunch spacings
- the option of colliding long super-bunches $\rightarrow$ lower heat load
- the possible use of higher harmonic RF systems or crab cavities
- magnet technology issues and alternative IR layouts

A new recipe for optimizing the luminosity of a collider near the beam-beam limit by increasing bunch length or crossing angle has been proposed. A feasibility report has been published.

Task Force on LHC Luminosity and Energy Upgrade

The task force had 5 meetings and included the following members:

O. Brüning, R. Cappi, R. Garoby, O. Gröbner, W. Herr, T. Linnecar, R. Ostojic, K. Potter, L. Rossi, F. Ruggiero (convener), K. Schindl, G. Stevenson, L. Tavian, T. Taylor, E. Tsesmelis, E. Weisse, and F. Zimmermann.

Other important, spontaneous contributions:

J. Gareyte → high harmonic RF system to shorten the bunches,
B. Jeanneret → beam-gas nuclear interactions and magnet quench limit, H. Grote → beam-beam tune footprints,
L. Bottura → ramp-rate limitations of pulsed SC magnets,
L. Bruno, P. Sala, and V. Mertens → beam dumping system,
G. Arduini → guided tour of the SPS tunnel to discuss installation of a pulsed SC ring on top of the existing SPS machine.

Early work of the Task Force

A random list of the top 10 key questions for the task force included:

1. minimum acceptable number of future LHC experiments?
2. maximum number of events per collision the detectors can swallow?
3. minimum acceptable distance from the last magnet to the IP?
4. maximum gradient and aperture of future LHC quadrupoles?
5. maximum crossing angle and minimum acceptable beam separation at the parasitic collision points?
6. maximum beam intensity on the beam dump at 8 and 14 TeV?
7. maximum field and energy swing of future LHC dipoles?
8. magnet quench limit for higher LHC beam energy?
9. maximum energy of the last LHC injector?
10. highest brilliance and intensity the injectors can deliver?

Answers to some key questions

1. The TWO high-luminosity pp experiments, ATLAS and CMS, and the one heavy-ion experiment ALICE, can potentially add to their physics reach from a Super-LHC. It is assumed that the detectors would be installed and ready in about 2012.

2. In their present configuration, the CMS and ATLAS detectors can accept a maximum luminosity of $3\text{-}5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

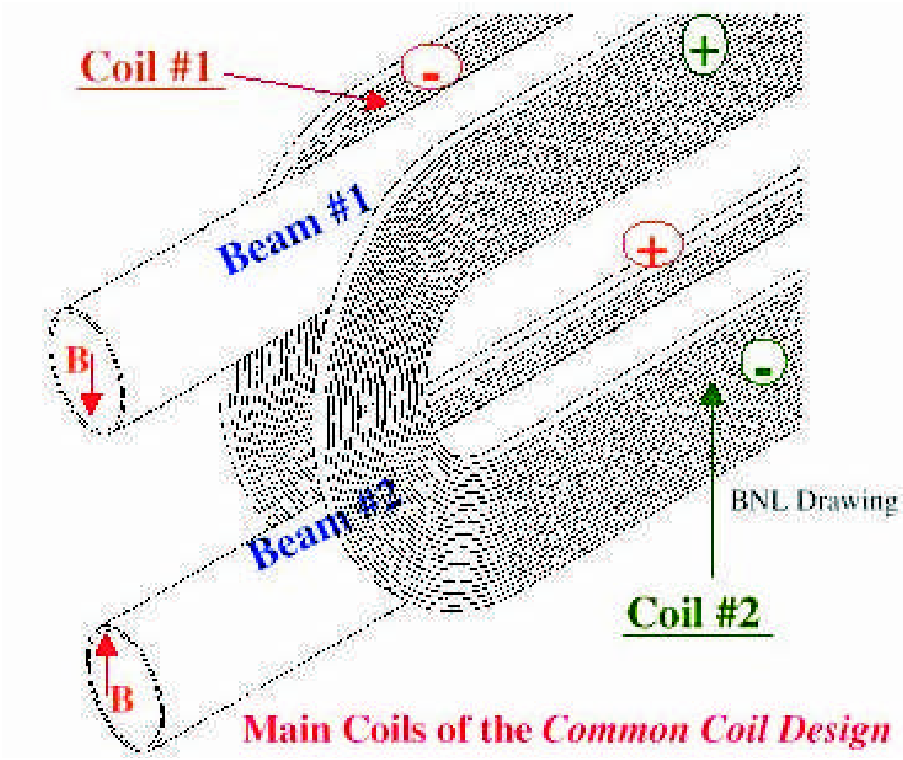
3. An increase in luminosity may require positioning the low-β quadrupoles closer to the IP than the current $\ell^* \simeq 23\,\mathrm{m}$. A re-design of the calorimeters, muon detectors and radiation shielding in the forward region would probably be needed.

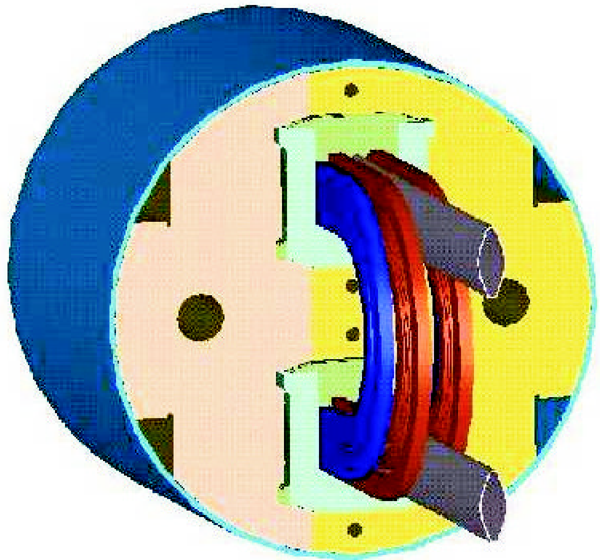
4. A maximum quadrupole gradient of 350–400 T/m with a 55–60 mm bore diameter can be reached.

5. The minimum acceptable beam separation depends on the square root of the brilliance $N_\mathrm{b}/\varepsilon_\mathrm{n}$ times the number of parasitic collisions.

6. Increasing the beam current from the nominal 0.56 to 0.85 A by raising the bunch intensity to 1.7×10^{11} p/bunch is still compatible with the present beam dumping system. Further increases, e.g. to 2×10^{11} p/bunch (corresponding to 1 A) or slightly higher, could still be tolerated accepting somewhat reduced safety margins or implementing moderate upgrades. Within the constraint of the existing tunnels and caverns, solutions for the beam dumping system could be found for beam currents up to at least 2 A. The energy deposition densities in the dump rise more than in proportion to the beam energy. An energy increase from 7 to 14 TeV would cause a temperature increase by a factor of 2.8.

7. Dipole magnets with a nominal field of 15 T and a safety margin of about 2 T can be considered a reasonable target for 2015 and could be operated by 2020. This requires a serious and vigorous R&D programme on new SC materials. At LBL there is a working prototype dipole magnet reaching 14.5 T (BNL design, common coil, cheap).





Sketch of the Common Coil design for a double aperture dipole magnet. The coils couple the two apertures and can be flat (no difficult ends). One of the most difficult challenges will be to make it at reasonable cost, less than 5 kEuro/(double)T.m say, including cryogenics, to be compared with about 4.5 kEuro/(double)T.m for the present LHC.

8. The ideal energy swing is around 3. A dynamic range an order of magnitude larger can be achieved, but would require more nonlinear correctors. Therefore one may consider the following 3 scenarios:
   - use the LHC as a pre-injector (energy swing 2–3)
   - fill the SPS with 3 T dipoles and double the LHC injection energy (energy swing around 15)
   - use the SPS to inject at 450 GeV (energy swing around 30)
9. The magnet quench limit with respect to beam losses depends on the field safety margin: Nb_3Sn is more stable than NbTi, high T_c materials may be even more interesting.
10. A possibility being considered also for CNGS beams is to upgrade the proton linac from 50 to 120 MeV (cost about 70 MCHF), to overcome space charge limitations at injection in the booster. Then the ultimate LHC intensity would become very easy to achieve and a further 30% increase would be possible, corresponding to a bunch intensity of 2×10^{11} p/bunch with almost the same emittance.

Luminosity optimization

short bunches of length $\sigma_z \ll \beta^* \Longrightarrow$ negligible 'hourglass effect',

peak luminosity for round beams colliding with full crossing angle θ_c

$$L = \frac{N_b^2 f_{rep}}{4\pi\sigma^{*2}} F \quad \text{reduced by a factor} \quad F \simeq 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

$f_{rep} = n_b f_o$: average bunch repetition frequency,
$\sigma^* = \sqrt{\varepsilon\beta^*}$: r.m.s. transverse beam size at the IP ($16\,\mu$m for LHC)

maximum luminosity below beam-beam limit $\Longrightarrow$ short bunches and minimum crossing angle (baseline scheme)

H-V crossings in two IPs $\Longrightarrow$ no linear tune shift due to long range

total linear beam-beam tune shift also reduced by a factor $F_{bb} \simeq F$ (for short bunches)

$$\Delta Q_{bb} = \xi_x + \xi_y = \frac{N_b r_p}{2\pi\varepsilon_n} F$$

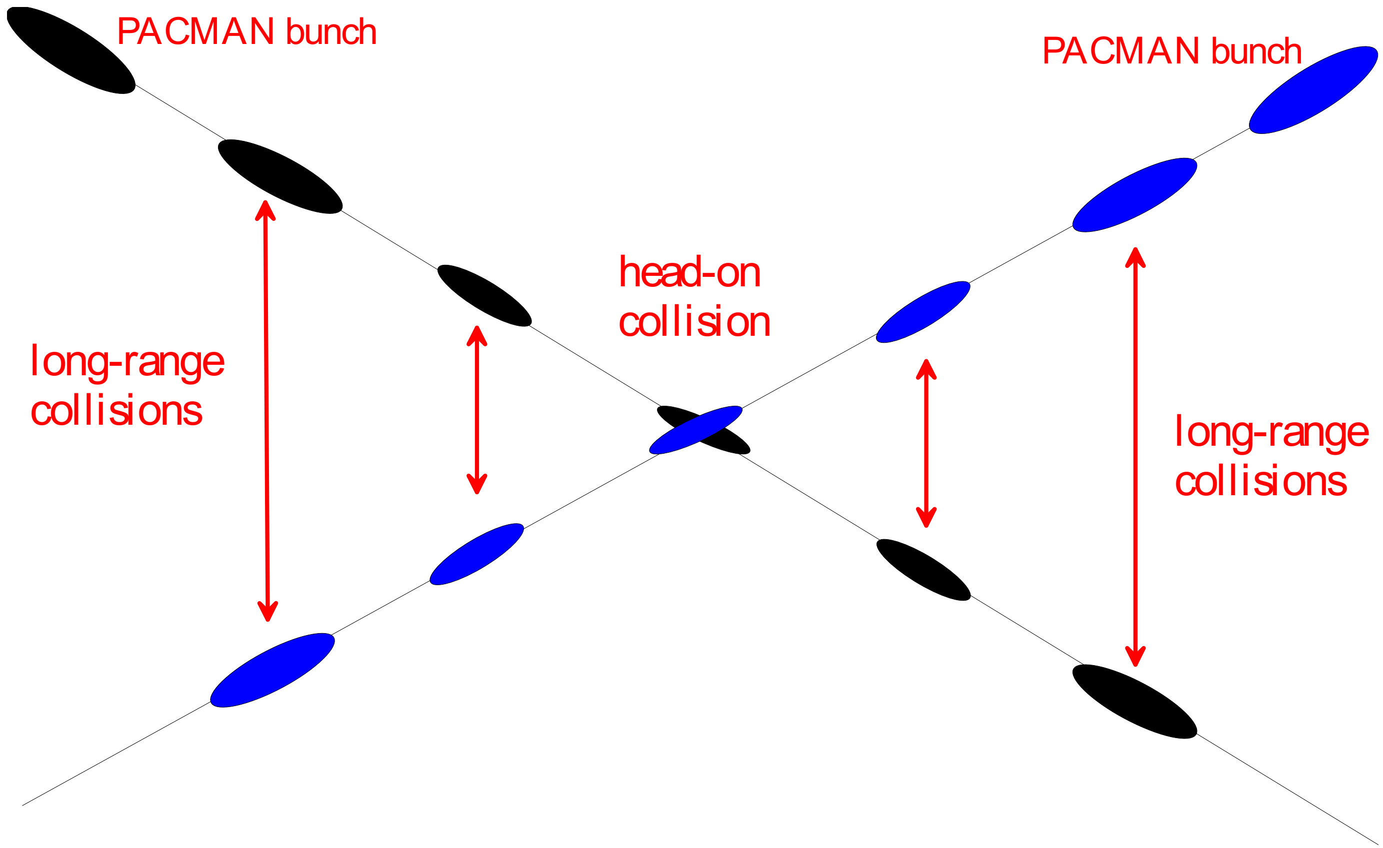
if bunch intensity and brilliance are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) $\Longrightarrow$ luminosity can be increased without exceeding the beam-beam limit $\Delta Q_{\mathrm{bb}} \sim 0.01$ by increasing the crossing angle and/or the bunch length

express beam-beam limited brilliance $N_{\mathrm{b}}/\varepsilon_{\mathrm{n}}$ in terms of maximum total beam-beam tune shift ΔQ_{bb}, then

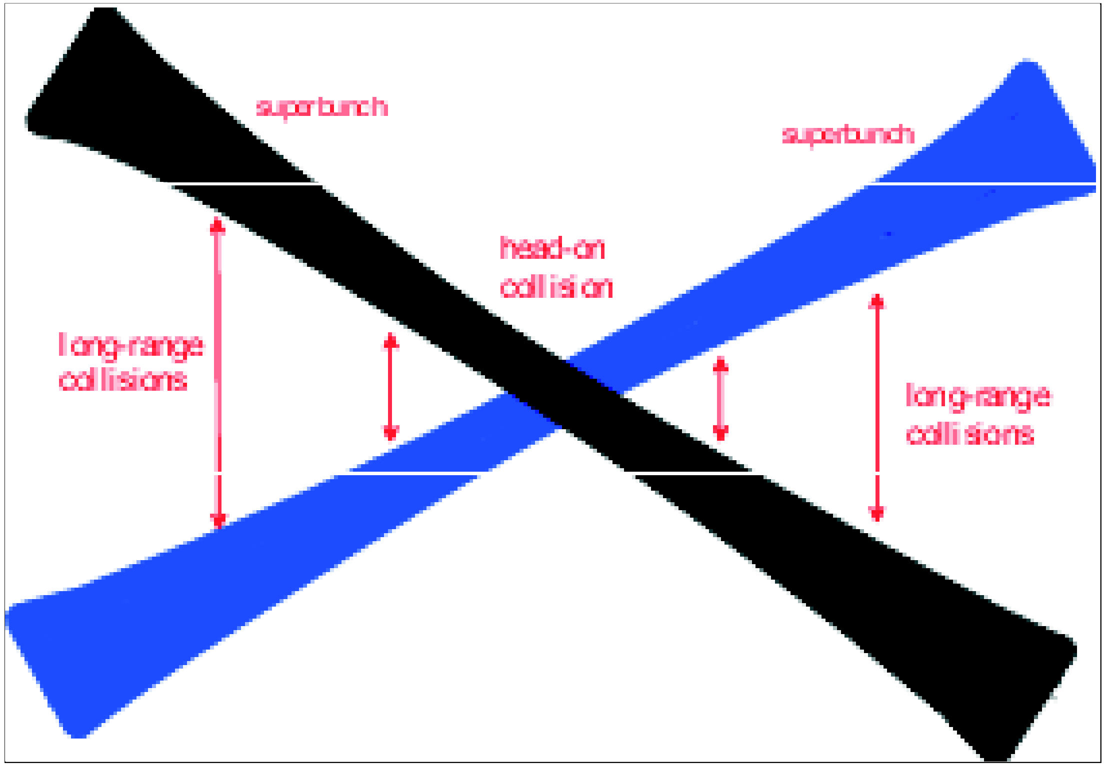
$$L \simeq \gamma \Delta Q_{\mathrm{bb}}^2 \frac{\pi \varepsilon_{\mathrm{n}} f_{\mathrm{rep}}}{r_{\mathrm{p}}^2 \beta^*} \sqrt{1 + \left(\frac{\theta_{\mathrm{c}} \sigma_z}{2\sigma^*}\right)^2}$$

luminosity is proportional to collision energy and normalized transverse emittance $\varepsilon_{\mathrm{n}} = \gamma\varepsilon \Longrightarrow$ an increased injection energy (Super-SPS) allows a larger normalized emittance and thus more intensity and more luminosity at the beam-beam limit

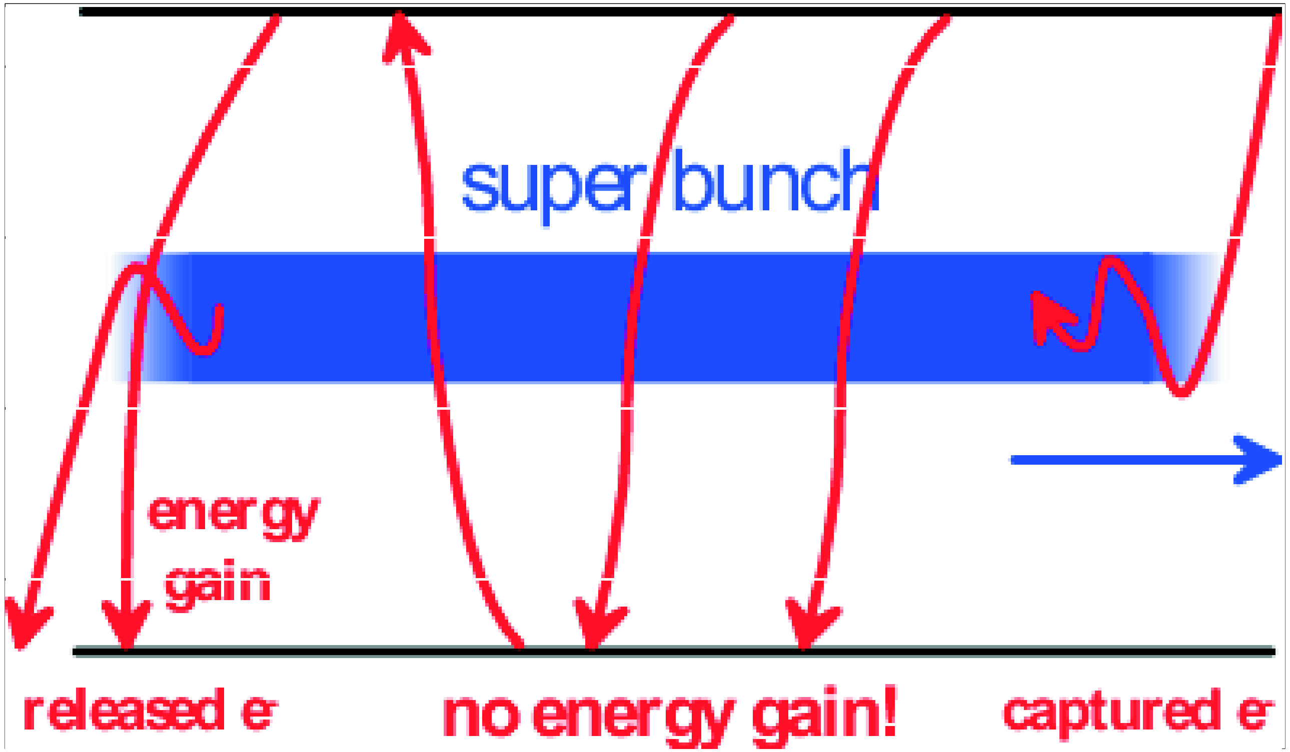
Another possibility to achieve significant luminosities with large crossing angles consists in colliding very long ‘super-bunches’.



Schematic of long-range collisions on either side of the main interaction point. (Courtesy W. Herr)



Schematic of a super-bunch collision, consisting of 'head-on' and 'long-range' components. The luminosity for super-bunches having flat longitudinal distribution is $\sqrt{2}$ times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population (see LHC Project Report 627).



Schematic of reduced electron cloud build-up for a super-bunch.
(Courtesy F. Zimmermann)

Minimum crossing angle

scaling law for 'diffusive aperture' $d_{\rm da}$ with long range collisions

$$(d_{\rm sep} - d_{\rm da})/\sigma \propto \sqrt{k_{\rm par}\, N_{\rm b}/\varepsilon_{\rm n}}$$

$d_{\rm sep}/\sigma \simeq \theta_{\rm c}/\sigma_\theta$: relative beam separation
$\sigma_\theta = \sqrt{\varepsilon/\beta^*}$: r.m.s. angular beam divergence at the IP

the ratio $(d_{\rm sep} - d_{\rm da})/\sigma$ is independent of β and beam energy; it is again a function of the brilliance $N_{\rm b}/\varepsilon_{\rm n}$. From particle tracking

$$d_{\rm da}/\sigma \simeq \theta_{\rm c}\sqrt{\beta^*/\varepsilon} - 3\sqrt{\frac{k_{\rm par}}{2\times 32}\,\frac{N_{\rm b}}{10^{11}}\,\frac{3.75\,\mu{\rm m}}{\varepsilon_{\rm n}}}$$

nominal LHC parameters $\theta_{\rm c} = 300\,\mu$rad and $\sigma_\theta = 31.7\,\mu$rad $\Longrightarrow$ $d_{\rm sep} \simeq 9.5\,\sigma$ and $d_{\rm da} \simeq 6 \div 6.5\,\sigma$. Preserving a comparable dynamic aperture with higher bunch intensities, shorter bunch spacings, and/or smaller β^* requires larger crossing angles

LHC Upgrade Scenarios

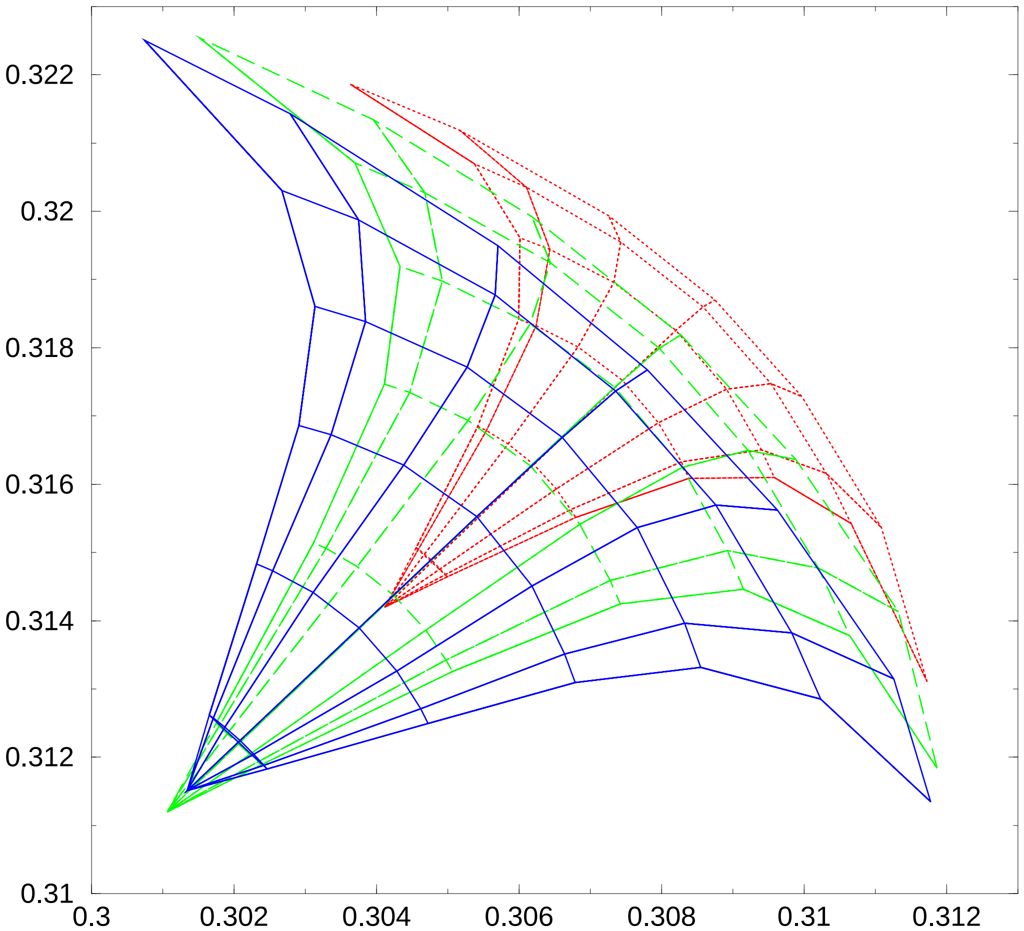
- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with 'major' hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes (LHC Phase 0) are:

1. collide beams only in IP1 and IP5 with alternating H-V crossing
2. increase N_b up to the beam-beam limit $\to L = 2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\to E_\mathrm{max} = 7.54\,\mathrm{TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

parameter	symbol	units	nominal	ultimate	Piwinski
number of bunches	n_{b}		2808	2808	2808
bunch spacing	Δt_{sep}	ns	25	25	25
protons per bunch	N_{b}	10^{11}	1.1	1.7	2.6
aver. beam current	I_{av}	A	0.56	0.86	1.32
norm. tr. emittance	ε_{n}	μm	3.75	3.75	3.75
long. emittance	ε_{L}	eV s	2.5	2.5	4.0
peak RF voltage	V_{RF}	MV	16	16	3/1
RF frequency	f_{RF}	MHz	400.8	400.8	200.4/400.8
r.m.s. bunch length	σ_z	cm	7.55	7.55	15.2
r.m.s. energy spread	σ_{E}	10^{-4}	1.13	1.13	0.9
IBS growth time	$\tau_{x,\mathrm{IBS}}$	h	111	72	87
beta at IP1-IP5	β^*	m	0.5	0.5	0.5
full crossing angle	θ_{c}	μrad	300	315	345
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	1.0	2.3	3.6



Comparison of tune footprints, corresponding to betatron amplitudes extending from 0 to 6 σ, for LHC nominal (red-dotted), ultimate (green-dashed), and large Piwinski parameter configuration (blue-solid) with alternating H-V crossing only in IP1 and IP5. (Courtesy H. Grote)

LHC Phase 1: Luminosity Upgrade

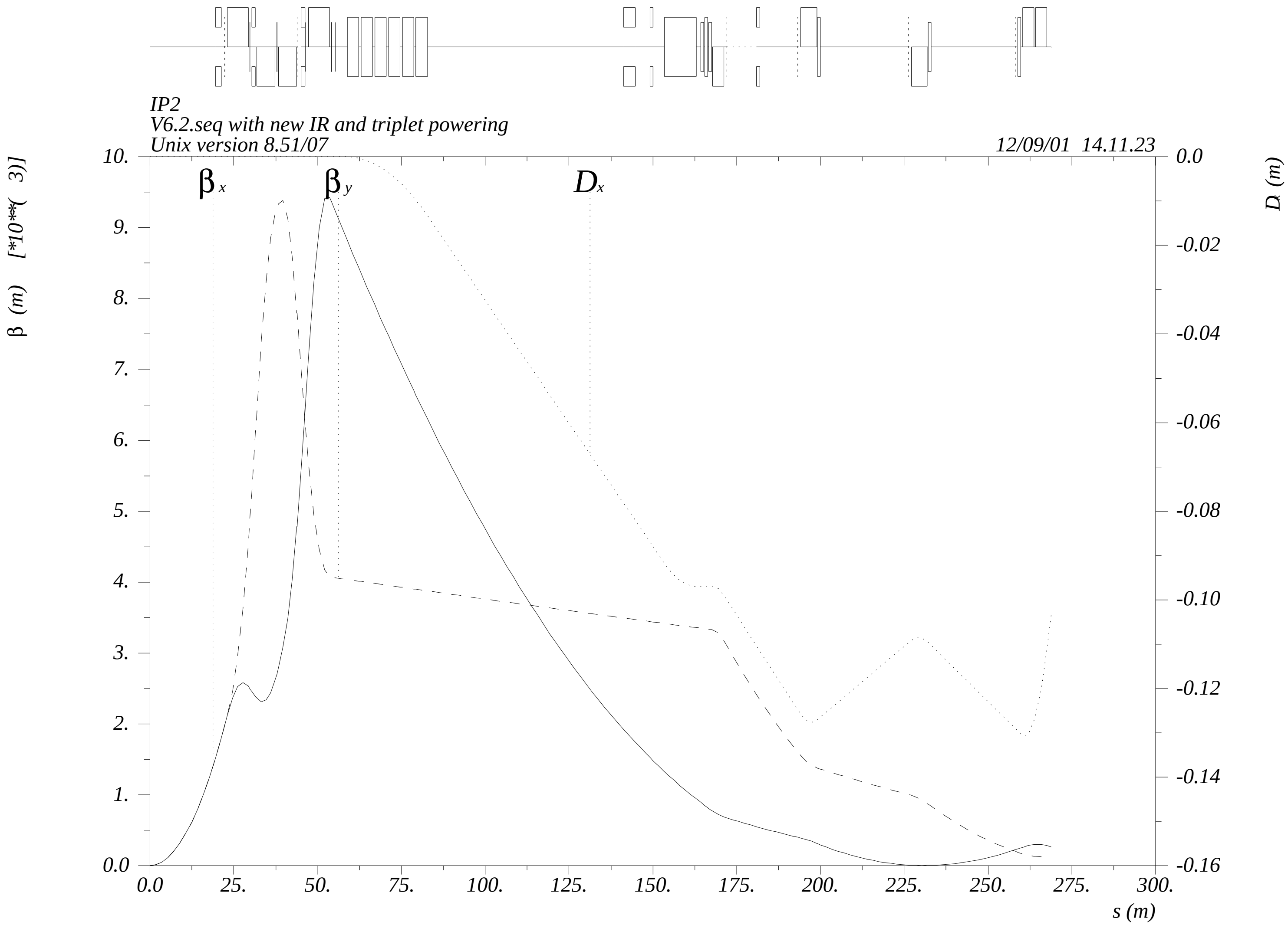
Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25\,\mathrm{m}$
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 424\,\mu\mathrm{rad}$
3. increase N_b up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
4. halve σ_z with high harmonic RF system $\rightarrow L = 4.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
5. double number of bunches (and increase θ_c!) $\rightarrow L = 9.4 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ excluded by electron cloud?

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-beam scattering growth time decreases by $\sqrt{2}$, from 60 h down to about 40 h.

parameter	symbol	units	baseline	Piwinski	super-bunch
number of bunches	$n_{\rm b}$		2808	2808	1
bunch spacing	$\Delta t_{\rm sep}$	ns	25	25	
protons per bunch	$N_{\rm b}$	10^{11}	1.7	2.6	5600
aver. beam current	$I_{\rm av}$	A	0.86	1.32	1.0
norm. tr. emittance	$\varepsilon_{\rm n}$	μm	3.75	3.75	3.75
long. emittance	$\varepsilon_{\rm L}$	eV s	1.78	2.5	15000
peak RF voltage	$V_{\rm RF}$	MV	43	16	3.4
RF frequency	$f_{\rm RF}$	MHz	1202.4	400.8	10
r.m.s. bunch length	σ_z	cm	3.78	7.55	7500
r.m.s. energy spread	$\sigma_{\rm E}$	10^{-4}	1.60	1.13	5.8
IBS growth time	$\tau_{x,\rm IBS}$	h	42	46	63
beta at IP1-IP5	β^*	m	0.25	0.25	0.25
full crossing angle	$\theta_{\rm c}$	μrad	445	485	1000
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	4.6	7.2	9.0

Optics functions for LHC Phase 1: baseline IR layout



The β-functions right from IP5 for $\beta^* = 0.25\,\mathrm{m}$.

Triplet aperture requirements: baseline scheme

rough estimate of triplet quadrupole aperture $D_{\rm trip}$ for $\ell^* = 23\,{\rm m}$:

- $9\,\sigma$ beam envelope
- $7.5\,\sigma$ beam separation
- 20% β-beating
- 4 mm spurious dispersion
- 3 mm peak orbit excursion
- 1.6 mm mechanical tolerances
- beam screen and cold bore

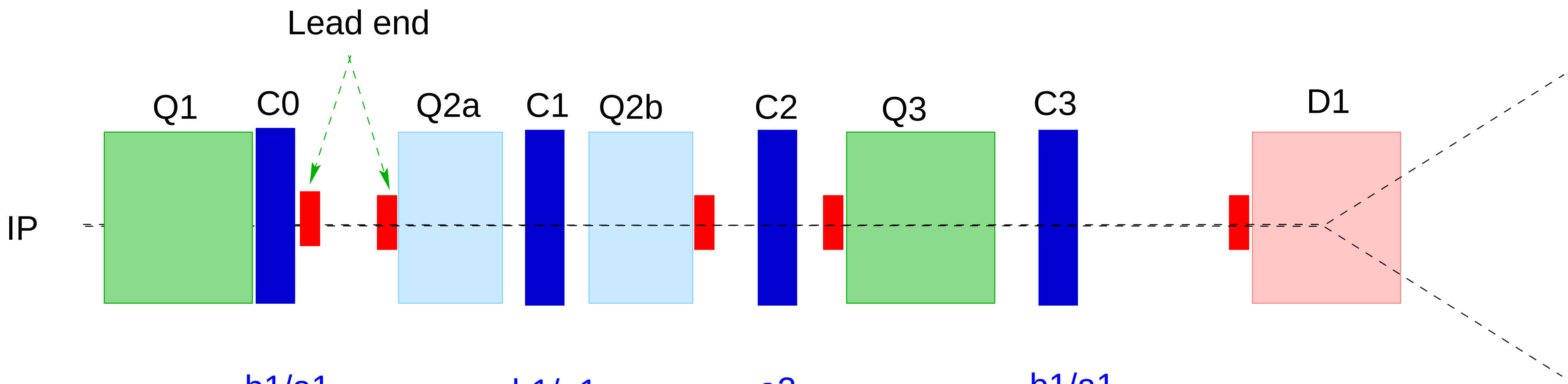
$$D_{\rm trip} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times 8.6\,{\rm mm}$$

$\beta^* = 0.5\,{\rm m} \rightarrow \sigma_{\rm max} \simeq 1.5\,{\rm mm} \Longrightarrow D_{\rm trip} > 60\,{\rm mm} \rightarrow$ <u>70 mm ID coil</u>

$\beta^* = 0.25\,{\rm m} \rightarrow \sigma_{\rm max} \simeq 2.2\,{\rm mm} \Longrightarrow D_{\rm trip} > 80\,{\rm mm} \rightarrow$ <u>90 mm ID coil</u>

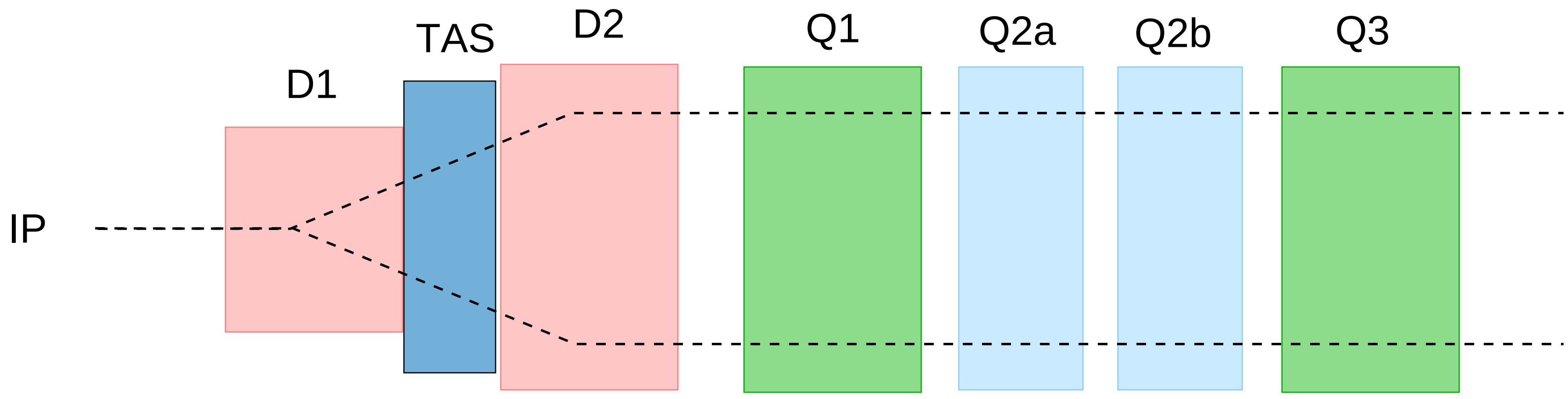
Triplet Correction Schemes

- *two possible schemes:*



	C0	C1	C2	C3	
	b1/a1	b1/a1	a2	b1/a1	
		b4 b5 a5	a3 a4 a6	b3 b6	: scheme 1
			a3 b4 a4	b3 b6	: scheme 2

Alternative IR layout for LHC Phase 1

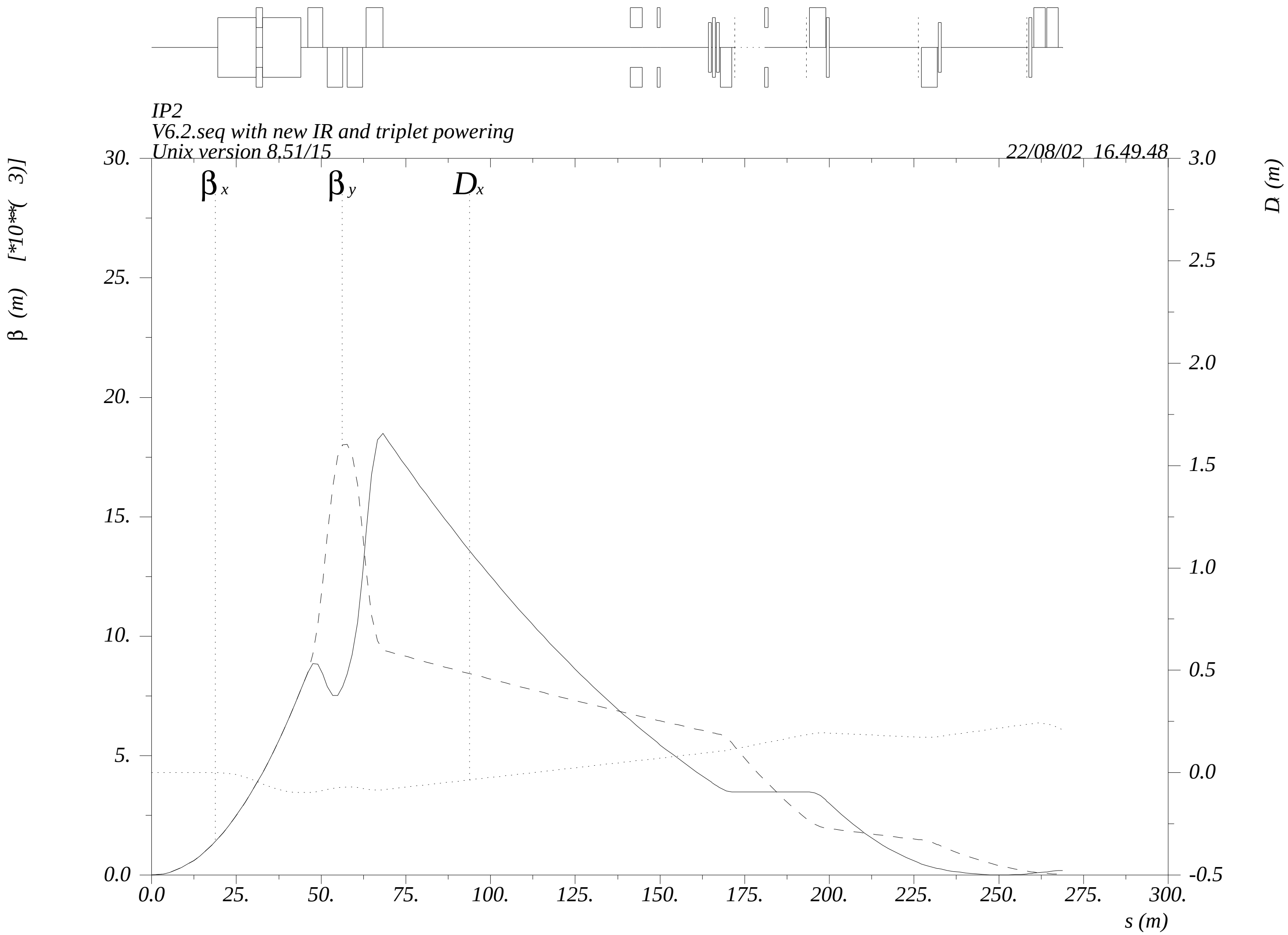


Sketch of a possible IR layout for an LHC luminosity upgrade with separation dipoles close to the IP and separated magnet bores inside the triplet magnets. (Courtesy O. Brüning)

Main advantages:

- reduce number of long range beam-beam interactions
- no crossing-angle bump inside the triplet magnets $\Longrightarrow$ no feed-down errors

Optics functions for LHC Phase 1: IR layout with D1-D2 first



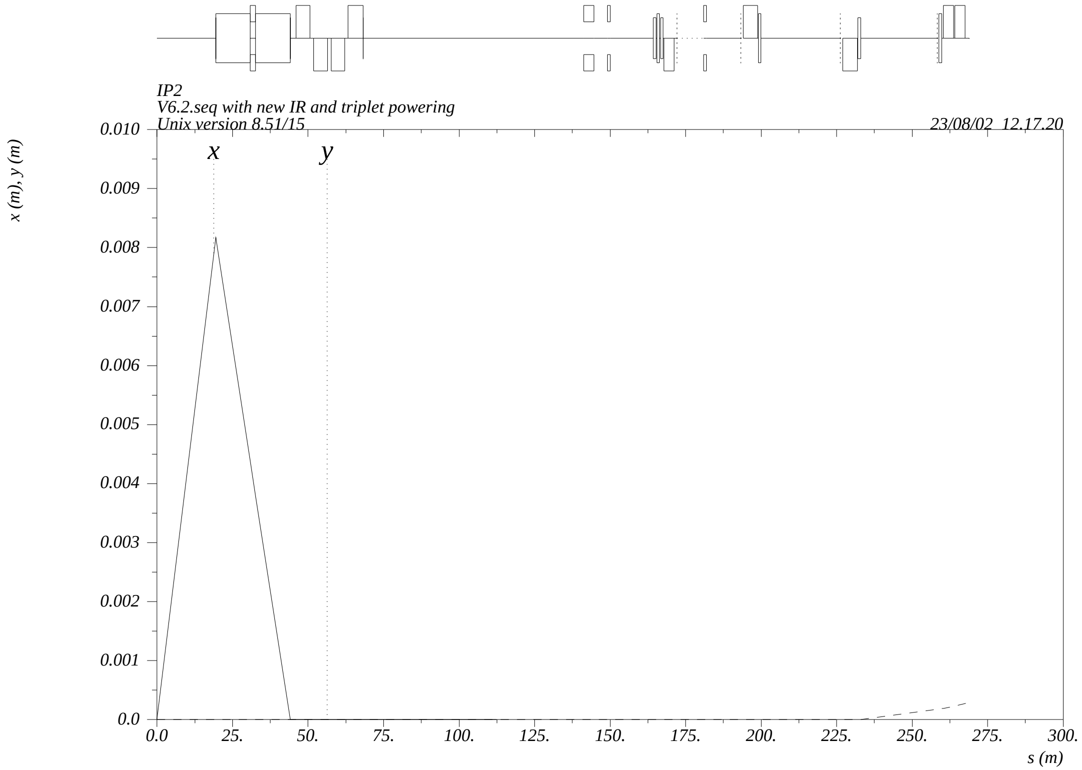
β-functions for $\beta^* = 0.25\,\mathrm{m}$ and triplets with separated bores.

Magnet requirements for alternative IR layout with $\beta^* = 0.25\,\mathrm{m}$

magnet	type	length	diameter range	beam separation	strength
D1	1 aperture	$11.4\,\mathrm{m}$	$34\,\mathrm{mm} \leftrightarrow 131\,\mathrm{mm}$	$0 \leftrightarrow 84\,\mathrm{mm}$	$15\,\mathrm{T}$
D2	2-in-1	$11.4\,\mathrm{m}$	$50\,\mathrm{mm} \leftrightarrow 60\,\mathrm{mm}$	$110\,\mathrm{mm} \leftrightarrow 194\,\mathrm{mm}$	$15\,\mathrm{T}$
Q1	2-in-1	$4.5\,\mathrm{m}$	$60\,\mathrm{mm} \leftrightarrow 70\,\mathrm{mm}$	$194\,\mathrm{mm}$	$230\,\mathrm{T/m}$
Q2	2-in-1	$2 \times 4.5\,\mathrm{m}$	$70\,\mathrm{mm} \leftrightarrow 78\,\mathrm{mm}$	$194\,\mathrm{mm}$	$257\,\mathrm{T/m}$
Q3	2-in-1	$5.0\,\mathrm{m}$	$70\,\mathrm{mm} \leftrightarrow 78\,\mathrm{mm}$	$194\,\mathrm{mm}$	$280\,\mathrm{T/m}$

Magnet parameters for a triplet layout with separated beams inside the triplet magnets. The beam separation does not include the additional separation from the crossing angle bump. We assume that the beam separation can be done via two $11.4\,\mathrm{m}$ long $15\,\mathrm{T}$ dipole magnets (possibly with high temperature superconducting coils).

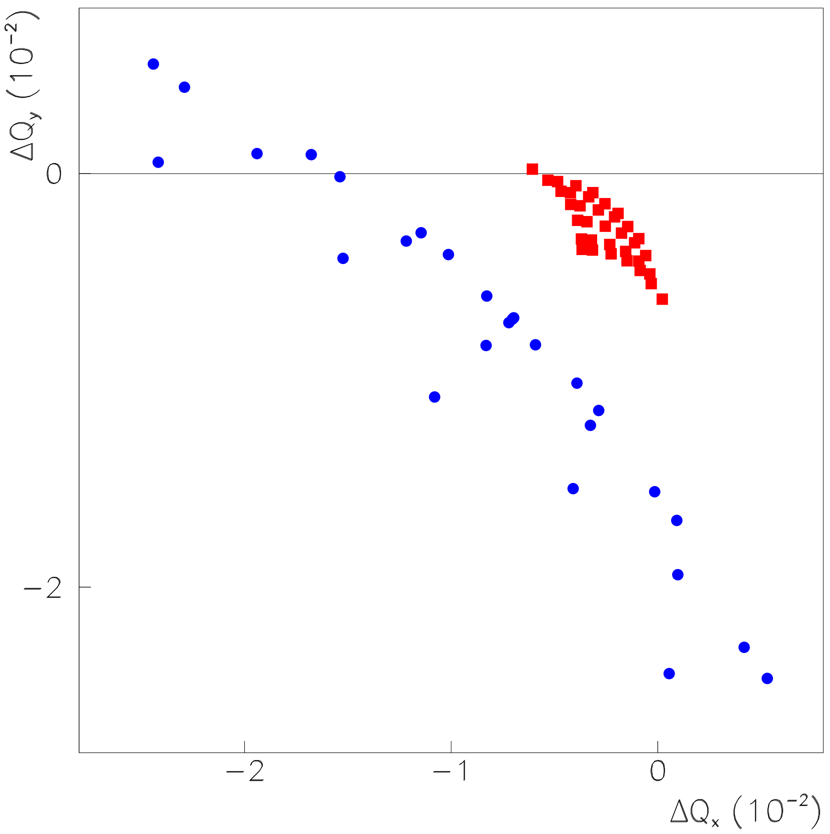
Crossing-angle orbit bump for alternative IR layout



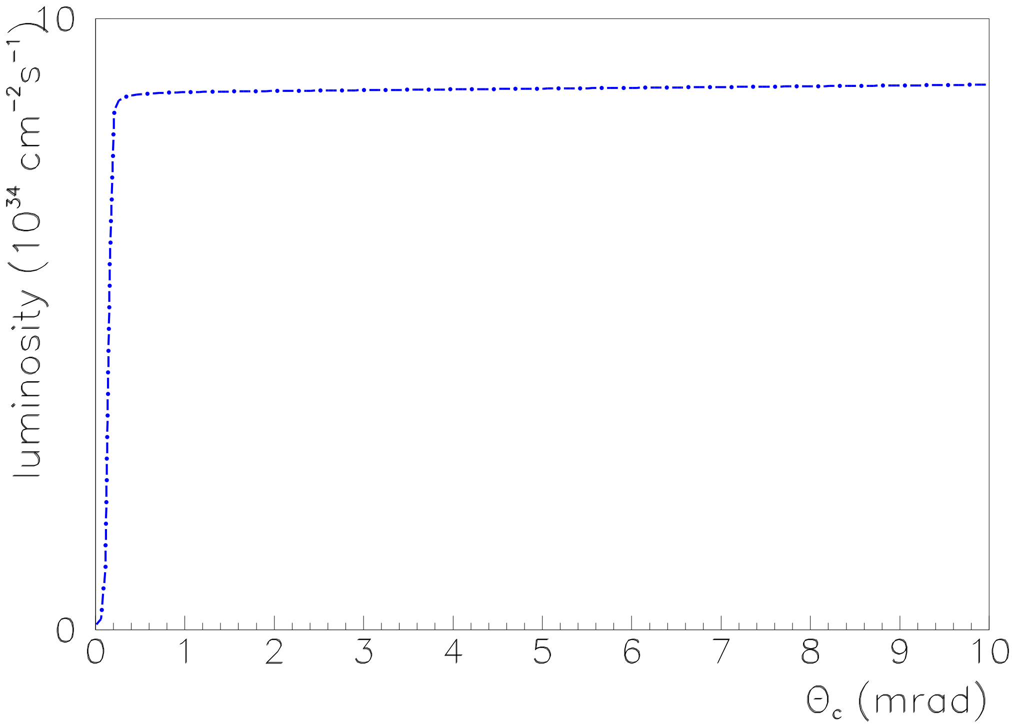
Horizontal crossing bump for $\beta^* = 0.25\,\mathrm{m}$ and triplets with separated bores: additional deflection angle of $750\,\mu$rad at D1 and $330\,\mu$rad at D2. reducing required dipole field strength by 10% and 4.5%, respectively. A vertical crossing can be generated by rotating the D1 and D2 magnets by 5.7° and 2.9°: available horizontal field strength reduced by less than 1%.

LHC Phase 2: Luminosity and Energy Upgrade

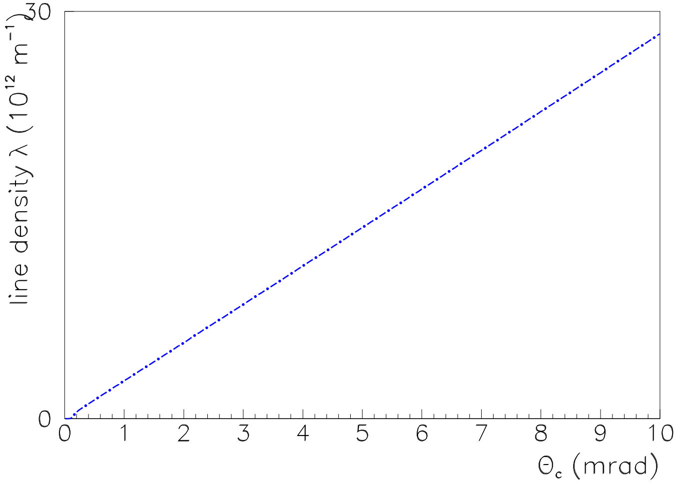
- Modify the injectors to significantly increase the beam intensity and brilliance beyond its ultimate value (possibly in conjunction with beam-beam compensation schemes).
- Equip the SPS with superconducting magnets, upgrade transfer lines, and inject into the LHC at 1 TeV. For given mechanic and dynamic apertures at injection, this option can increase the LHC luminosity by nearly a factor two, at constant beam-beam parameter $N_\mathrm{b}/\varepsilon_\mathrm{n}$, in conjunction with long range b-b compensation schemes. This would also be the natural first step in view of an LHC energy upgrade $\Longrightarrow$ energy swing reduced by a factor 2. Interesting alternative $\Longrightarrow$ cheap, compact low-field booster rings in the LHC tunnel.
- Install new 15 T superconducting dipoles in the LHC arcs to reach a beam energy around 12.5 TeV.

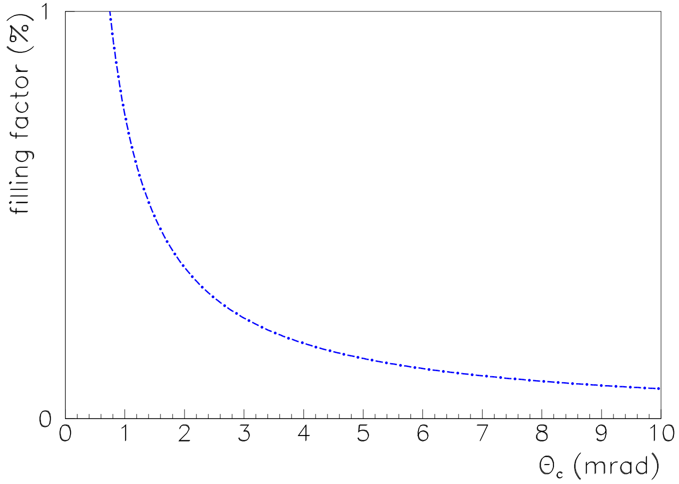


Tune footprints for super-bunches colliding under two different crossing angles: $\theta_c = 400\,\mu$rad (blue circles) and $\theta_c = 1\,$mrad (red squares). The points represent the tune shifts at betatron amplitudes extending from 0 to $6\,\sigma$. Other parameters: line density $\lambda = 8.8 \times 10^{11}\ \mathrm{m}^{-1}$, $\beta^*_{x,y} = 0.25\,$m, super-bunch length $l = 40\,$m. (Courtesy F. Zimmermann)



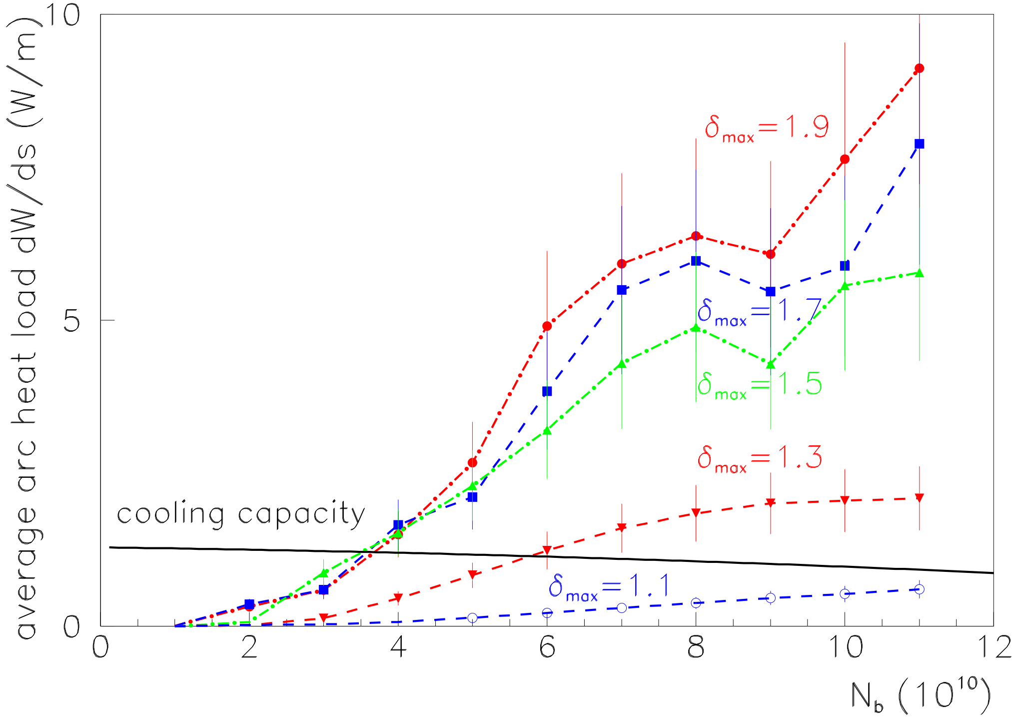
Luminosity for super-bunches with $|\Delta Q_x + \Delta Q_y| = 0.01$ and intensity $I_{\mathrm{beam}} = 1\,\mathrm{A}$ vs. crossing angle. The luminosity increases linearly with beam current. With a crossing angle of a few mrad, a 300 m long super-bunch in each LHC ring would be compatible with the beam-beam limit and the corresponding luminosity in ATLAS and CMS (with alternating H-V crossings) would be about $9 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.



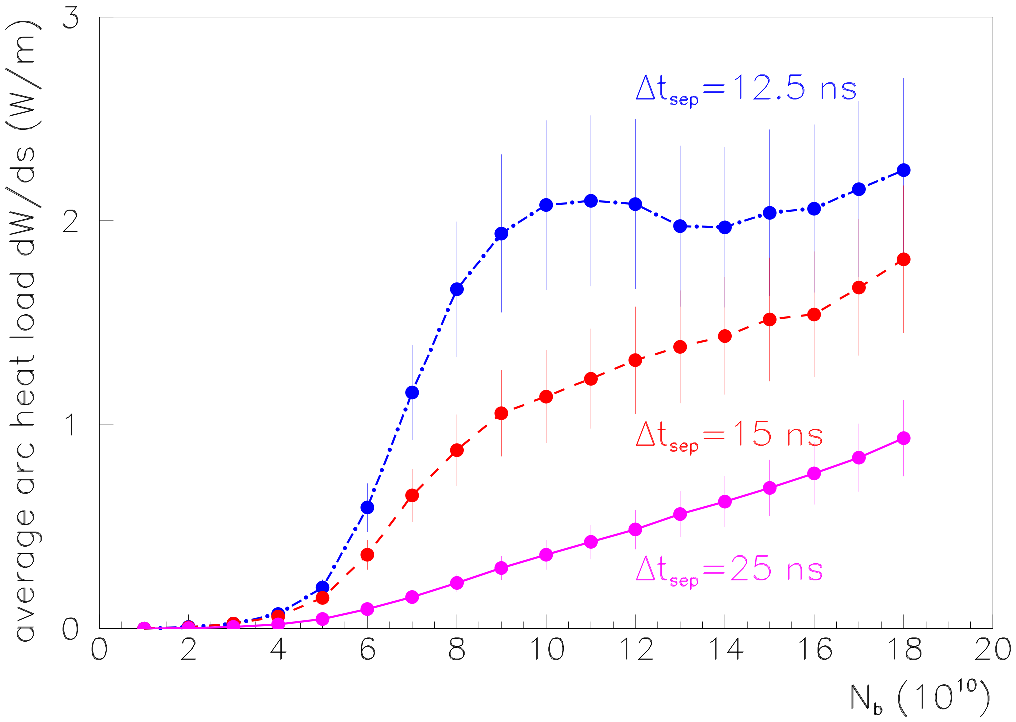


Line density for $|\Delta Q_x + \Delta Q_y| = 0.01$ (left) and resulting filling factor f for $I_{\rm beam} = 1\,{\rm A}$ (right), vs. crossing angle. The filling factor increases linearly with beam current.

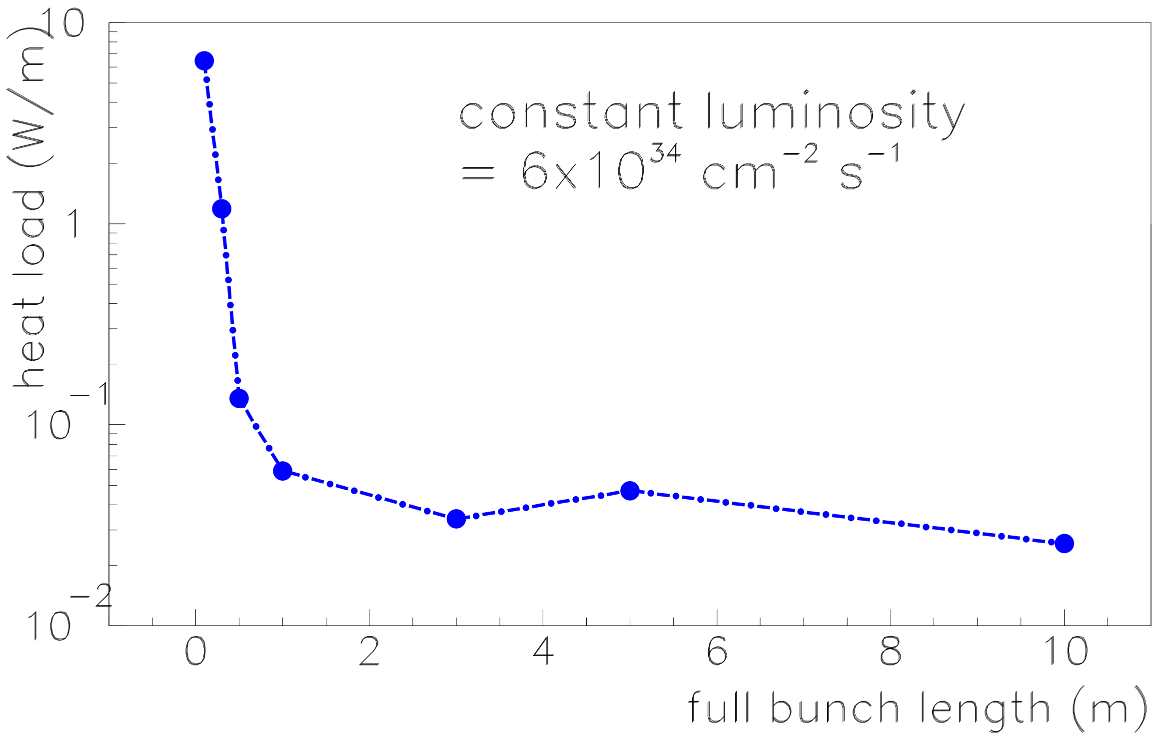
Keeping the total beam current constant, and also limiting the total tune shift from two interaction points $|\Delta Q_{\rm tot}| = |\Delta Q_x + \Delta Q_y|$ to a value of 0.01, the line density λ and the filling factor f are uniquely defined as a function of crossing angle. (Courtesy F. Zimmermann)



Average arc heat load due to electron cloud and LHC cooling capacity as a function of bunch population N_b, for 25 ns bunch spacing and various values of $\delta_{\max}$. Other parameters are $\epsilon_{\max} = 240$ eV, $R = 5\%$, $Y = 5\%$, and elastic electron reflection is included, parametrized by a Gaussian probability distribution centered at zero primary energies with a peak value of $\delta_{el,E} = 0.56$ and a standard deviation $\sigma_{el} = 52\,\mathrm{eV}$.



Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{\max} = 1.1$. Elastically reflected electrons are included. (Courtesy F. Zimmermann)



Simulated heat load in an LHC arc dipole due to the electron cloud as a function of super-bunch length for $\delta_{\max} = 1.4$, considering a constant flat top proton line density of 8×10^{11} m^{-1} with 10% linearly rising and falling edges. The number of bunches is varied so as to keep the luminosity constant and equal to $6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Recommendations for future studies and R&D

nominal LHC performance is challenging (not to mention ultimate) $\Longrightarrow$ learn how to overcome electron cloud effects, inject, ramp, and collide almost 3000 high intensity bunches, protect superconducting magnets, safely dump the beams, etc.

the CERN feasibility study has not addressed magnetic field quality, required upgrades of beam instrumentation, collimation and machine protection, and flat beam schemes at 7 TeV. To reduce collimator impedance during β-squeeze and physics, triplet aperture should be i) LARGE and ii) possibly protected by local tertiary collimators

upgrades in beam intensity (and brilliance) are a viable option, require R&D for cryogenics, vacuum, RF, beam dump, and injectors, and operation with large crossing angles $\Longrightarrow$ new triplet quadrupoles with high gradient and larger aperture (or alternative IR layouts) are needed for the LHC luminosity upgrade. Opening the quads has the additional advantage of letting through the radiation

Further experimental studies on electron cloud, long range, and strong-strong beam-beam effects are important, as well as MDs in existing hadron colliders with large Piwinski parameter and many bunches $\Longrightarrow$ international collaboration (e.g. US-LHC, ESGARD) is welcome/needed for LHC machine studies/commissioning

beam-beam compensation schemes with pulsed wires would reduce tune footprints and loss of dynamic aperture due to long range collisions $\Longrightarrow$ need experimental validation

Interesting possibilities currently under study to pass each beam through separate final quadrupoles include: alternative beam separation schemes with separation dipoles in front of the triplet quadrupoles and collision of long super-bunches with very large θ_c. With a crossing angle of a few mrad, a 300 m long super-bunch with intensity $I_{\mathrm{beam}} = 1\,\mathrm{A}$ in each LHC ring would be compatible with the beam-beam limit. The corresponding luminosity in ATLAS and CMS (with alternating H-V crossings) would be $9 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The super-bunch option is interesting for large crossing angles, can potentially avoid electron cloud effects and minimize the cryogenic heat load. One could inject a bunched beam, accelerate it to 7 TeV, and then use barrier buckets to form about 100 long super-bunches to reduce pile-up noise in the experiments.

a major and sustained R&D effort on new SC materials and magnet design is needed for any LHC performance upgrade $\Longrightarrow$ foster and extend collaboration with other labs: new low-β quadrupoles with high gradient and larger aperture based on Nb_3Sn superconductor require 9-10 years for short model R&D and component development, prototyping, and final production.

An increased 1 TeV injection energy into the LHC in conjunction with beam-beam compensation schemes would yield a luminosity gain $\Longrightarrow$ a pulsed Super-SPS (and new SC transfer lines) or cheap low-field booster rings in the LHC tunnel could be the first step for an LHC energy upgrade.